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WATERSHED LEVEL BEST MANAGEMENT PRACTICE SELECTION AND PLACEMENT IN THE TOWN BROOK WATERSHED, NEW YORK[1]

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ABSTRACT: For a number of years, best management practices (BMPs) have been implemented within the Town Brook watershed as part of a watershed wide effort to reduce phosphorus losses to the New York City water supply reservoirs. Currently, there are no quantitative indications of the effectiveness of these practices at the watershed scale. Additionally, work is needed to evaluate management practice solutions for costs in relation to effectiveness. In this study we develop a methodology for evaluating management solutions to determine the best way(s) to select and place management practices so that pollutant removal targets are met at minimum cost. The study combines phosphorus losses as simulated by the Soil and Water Assessment Tool (SWAT), management practice effectiveness estimates from a predeveloped characterization tool, and practice costs in optimizations using a genetic algorithm. For a user defined target phosphorus removal (60 percent for this study), optimization favors nutrient management plans, crop rotations, contour strip cropping, and riparian forest buffers; the most cost effective scenario achieves a cost effectiveness of $24/kg phosphorus removal per year compared to the $34/kg phosphorus removal per year associated with the current basic implementation scheme. The study suggests that there is a need to evaluate potential solutions prior to implementation and offers a means of generating and evaluating the solutions.
(KEY TERMS: BMP effectiveness; nonpoint source pollution; optimization; SWAT; simulation.)

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INTRODUCTION

The New York City water supply watersheds cover 5,100 km^2 (≈ 1,970 mi^2) in eight counties in New York State north and northwest of the city and contain 19 reservoirs and three controlled lakes (WAC, 1997; NYCDEP, 2000, 2002). The New York City water supply has three main reservoir systems: the Croton system east of the Hudson River and the Catskill and Delaware systems west of the Hudson. These systems provide approximately 4.9 billion liters (1.3 billion gal) of water daily to more than eight million people, including New York City residents, visitors, commuters, and residents of surrounding counties (WAC, 1997; NYCDEP, 2000, 2002). The Catskill/Delaware systems supply about 90 percent of the city's water (WAC, 1997; NYCDEP, 2000). The Croton system is a much older system, dating back to the 1800s, and does not have major agricultural pollution related problems (NYCDEP, 2000). Interest related to agricultural pollution is greater within the Catskill/Delaware region.

Dairy farming is the largest industry in the Catskill/Delaware watersheds. Crop agriculture – primarily pasture, corn, and hay – supports dairy farming. The major land use, though, is forestry, accounting for about 75 percent of land use in the Catskill/Delaware region. Forestry poses little to no threat to water quality; the key concern is pollution from agricultural lands (WAC, 1997).

Water quality problems commonly observed in the reservoirs include eutrophication, high levels of

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coliform bacteria, and turbidity (Tone *et al.,* 1997; WAC, 1997). Eutrophication, the enrichment of surface waters with plant nutrients and the subsequent abundant growth of plants within the waters (Frere *et al.,* 1980; FAO, 1996), is the principal concern (Tone *et al.,* 1997).

The Cannonsville Reservoir (Figure 1, inset) in the Catskill/Delaware system is affected by eutrophication. Agriculture, wastewater treatment plants, and urban runoff are considered responsible for the high nutrient levels in this reservoir (Tone *et al.,* 1997; WAC, 1997), with phosphorus (P) being the primary nutrient of concern. Excessive phosphorus loadings to the reservoir are thought to be largely the result of manure generated on surrounding farms. The manure is either accumulated in barnyards or applied to the land (WAC, 1997).

Efforts to address this problem led to a partnership between farmers and the city and subsequently to the development of a Watershed Agricultural Program that is implemented by the Watershed Agricultural Council. The main goal of the program is to protect the New York City water supply while also maintaining the viability of the agricultural industry. Under the program, BMPs are being implemented on most farms within the watersheds, including cropland BMPs such as strip cropping and crop rotations and other BMPs focused on livestock facilities. The latter include diversions and barnyard BMPs such as paving, manure pack management, and filter strips.

Currently there are no quantitative indications of the effectiveness of BMPs at the watershed scale, with effectiveness defined as the percentage by which BMPs reduce phosphorus. Information also is limited regarding which BMPs are having beneficial effects and whether all BMPs are needed. Additionally there is need to determine the cost effectiveness of current and alternative solutions with a view to developing economical BMP implementation strategies. This study was aimed at developing a methodology for evaluating BMP solutions so as to determine the effectiveness of BMPs at the watershed scale and the

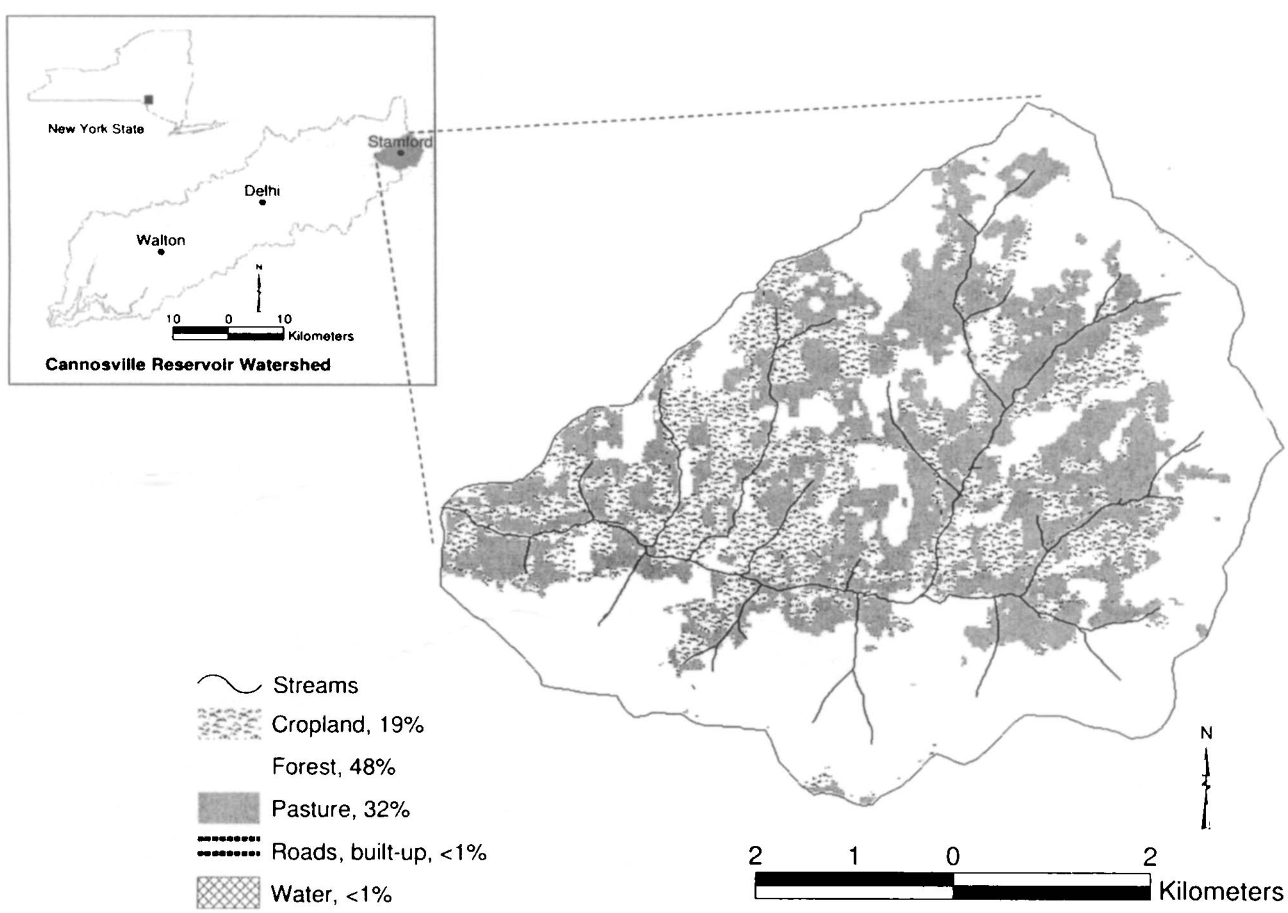

Figure 1. Town Brook Watershed Location and Land Use.

best way or ways to select and place BMPs so that pollutant removal targets are met at minimum cost.

The methodology developed uses SWAT (Arnold *et al.,* 1998), a BMP tool (Gitau *et al.,* 2005), BMP costs, and a genetic algorithm (Goldberg, 1989) to assess BMP effectiveness and determine optimal scenarios for BMP selection and placement. SWAT is a continuous simulation daily time step watershed model capable of simulating water and pollutants at locations within the watershed and at the watershed outlet. The SWAT model was used to characterize phosphorus loss from the variety of land use and soil combinations within the watershed. The BMP tool was developed to provide literature-based estimates of BMP effectiveness (i.e., the percentage of baseline loads by which phosphorus is reduced) based on site soils and slopes. Genetic algorithms are robust search algorithms that are suitable for optimizations involving complex problems with multiple solutions. The genetic algorithm was used to determine the best scenarios for BMP selection and placement in the watershed by combining baseline phosphorus loadings as simulated by SWAT, BMP effectiveness estimates from the BMP tool, and costs associated with the BMPs.

While the BMP implementation effort has been focused on the Cannonsville region, this study focused on the Town Brook watershed (Figure 1), a 3,700 ha (14 mi^2) watershed that is considered representative of upland conditions within the Cannonsville Reservoir watershed. The study, thus, sets the stage for similar evaluations for the Cannonsville Reservoir watershed and other watersheds that feed the New York City water supply system. The methodology developed pertains specifically to the Town Brook watershed, but the processes and procedures can be applied regardless of the watershed for which BMP solutions are being evaluated.

Watershed Description

The Town Brook watershed is in Delaware County, New York (latitude 42°21'36" N, longitude 74°36'00" W). The watershed is largely forested, and forest accounts for 48 percent of the land use by area (Figure 1). The principal industry is dairy farming. Crop agriculture supports dairy farming, mainly pasture (32 percent of land use) and corn and hay (in rotation, 19 percent). Land use on the remaining 1 percent is comprised of roads, ponds, and built-up areas. Average annual precipitation (a 37-year average) in this region is approximately 1,000 mm. Precipitation occurs throughout the year, with long term monthly averages ranging between 50 mm and 110 mm. Soils in the watershed are mainly silt loams dominated by the Lewbeach and Willowemoc series, which cover about 48 percent of the watershed and are generally shallow. The climate is characterized by low to moderate temperatures; long term means range from about -6°C (21°F) in January to 19°C (66°F) in July. The topography is characterized by steep ridges and narrow valleys, with slopes ranging from 0 to 40 percent. Elevations in the watershed range from 500 m above sea level at the watershed outlet to 982 m above sea level on the ridge tops.

MATERIALS AND METHODS

The methodology has four components: characterization of phosphorus losses from individual response units using SWAT; quantitative estimation of BMP effectiveness; determination of BMP costs; and optimization of BMP selection and placement. The four components, the relationships among them, and their application are summarized in Figure 2.

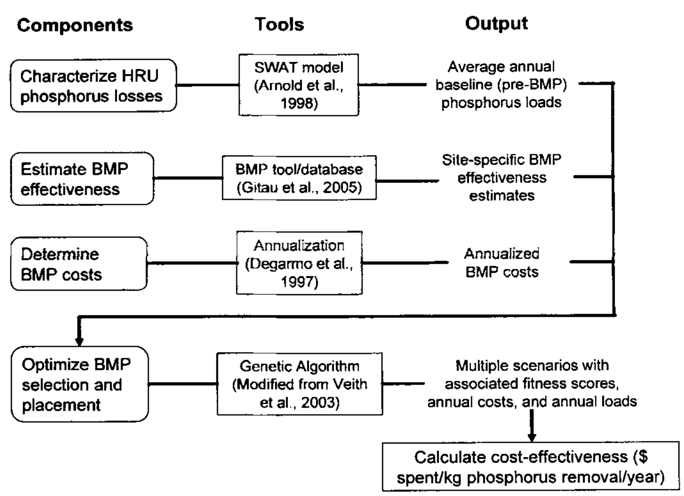

Figure 2. Flow Chart Summarizing Study Components, Links Between Components, and Study Output.

Characterization of Phosphorus Losses From Individual Units Within the Watershed

As an initial step, average annual baseline (pre-BMP) phosphorus losses from the watershed were determined on an individual response unit basis using SWAT. The SWAT model was chosen primarily because it allows identification of discrete response areas within a watershed while also offering flexibility in discretizing these areas.

The Soil and Water Assessment Tool. SWAT (Arnold *et al.,* 1998) is a continuous simulation daily time step river basin scale or watershed scale nonpoint pollution model. It incorporates features of several models including the Simulator for Water Resources in Rural Basins (SWRRB) (Williams *et al.,* 1985; Arnold *et al.,* 1990), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel *et al.,* 1980), Ground Water Loading Effects on Agricultural Management Systems (GLEAMS) (Leonard *et al.,* 1987), and Erosion Productivity Impact Calculator (EPIC) (Williams *et al.,* 1984; Williams, 1995). SWAT simulates water movement, sediment loss, and nutrient losses at locations within the watershed and at the watershed outlet.

With SWAT, the watershed is first divided into subwatersheds and then into hydrologic response units (HRUs), the discrete units upon which the model performs its analyses. The HRUs are defined based on user specified land use and soil area distribution thresholds expressed as percentages. Land uses that occupy a larger percentage than the specified land use threshold are considered unique land uses, while soils occupying percentages larger than the specified soil thresholds within the land uses designated as unique are considered unique soils. Land use and soil areas falling below the threshold values are lumped proportionately within the pre-identified land use and soil areas. Land use and soil thresholds can be lowered to lessen the lumping; setting both thresholds to zero precludes any lumping.

Base input data required to run SWAT includes weather (precipitation, temperature, solar radiation, wind speed, and relative humidity), land use, soils, and topography. Included with the SWAT model are built-in weather and soils databases from which data can be used in the absence of watershed specific data. The model also has a built-in weather generator for generating weather data if desired. The model provides defaults for most of the other input parameters, such as those pertaining to management, crop growth, and water quality. However, entering known or measured values where available and calibrating unknown parameters could help improve watershed representation and thus overall model accuracy.

The SWAT model provides output at the watershed, subbasin, and HRU level on a daily, monthly, and annual basis. This study used average annual HRU level output because the goal was to evaluate BMPs on an HRU basis and so as to correspond to BMP tool estimates that represent BMP effectiveness over time.

Input Data Preparation. Base topography, land use, and Soil Survey Geographic level soils data were obtained from the New York City Department of Environmental Protection (NYCDEP). In particular, a 10 m digital elevation model (DEM) provided the base elevation data needed for watershed definition and subdivision, and base land use data were extracted from a 10 m land use classification grid derived from Landsat thematic mapper (TM) imagery. Detailed soil components and layer properties not available within the base data were obtained from the National Soils Data Access Facility (http://www.statlab.iastate.edu, now http://soils.usda.gov). These data were preprocessed through area weighting of component data to give average values reflective of the soil map units. Soil bulk density, saturated hydraulic conductivity, rock fragment, and available water capacity data from the National Soils database were replaced with data from Cornell University laboratories that were specifically collected for the Town Brook watershed and were thus deemed more representative of conditions in the watershed.

Base weather data were obtained from the National Climate Data Center database (http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html). Precipitation data were obtained from the Stamford weather station located within the watershed, while temperature data were taken from the next nearest station, Delhi (Figure 1), as Stamford did not have sufficient temperature data for making the necessary SWAT runs.

By default, SWAT assigns slopes to each HRU while building the input data files. However, it performs the computations on a subbasin basis and assigns the same slope value to all HRUs within a subbasin regardless of their positioning in the landscape or actual slope. Slope affects water flow and nutrient transport and is a key input to the BMP tool. Consequently, HRU specific slopes were calculated using the DEM. The calculated slopes were used to replace SWAT calculated slopes. SWAT calculated channel dimensions were also replaced with measured values.

Other inputs including those pertaining to management, such as planting, harvesting and manure application, were based on information from Delaware County personnel regarding current practices within the watershed (D. Dewing, Watershed Agricultural Program, 2003, personal communication), from Natural Resources Conservation Service (NRCS) personnel (G. Lamont, NRCS, 2003, personal communication), and from Cornell Cooperative Extension (CCE, 1987).

Definition of Hydrologic Response Units. SWAT defines HRUs based on user defined land use and soil thresholds, as previously described. For this study, 0 percent land use and 0 percent soil thresholds were used (0/0 percent definition) to preserve all soils and land uses. This is important when characterizing phosphorus losses from individual HRUs, as potentially high phosphorus loss areas might be lost if lumping is allowed. Additionally, a 0/0 percent definition allows us to give HRUs a spatial definition, making it easier to visually display the HRUs and associated spatial data.

Calibration and Validation. The SWAT model was calibrated and validated for the Town Brook watershed. Calibrations were based on sensitivity analyses of potentially critical parameters as identified from Peterson (1997), White (2001), and Neitsch *et al.* (2002) and from observations made on uncalibrated runs. Parameters found sensitive included hydrology parameters such as the curve number, base flow recession, and snowmelt factors; sediment parameters such as the slope length and mixing efficiencies; and phosphorus related parameters such as the phosphorus partitioning coefficient and the phosphorus availability index. Parameters found sensitive were varied sequentially during calibrations as detailed in Gitau (2003). Model validations were carried out only for hydrology simulations, as available measured sediment and phosphorus data were insufficient to allow both calibration and validation.

Model performance was evaluated at the HRU level and at the watershed outlet. Model performance at the HRU level was considered important, as this was the level at which BMP effectiveness was evaluated. Model performance at the watershed outlet was considered primarily for hydrology simulations, as hydrology is the primary driver for other watershed processes.

Model performance at the HRU level was determined by comparing average annual HRU loads, summarized by land use, to watershed estimates for Delaware County (G. Lamont, NRCS, 2003, personal communication) and to loads published in the literature (CCE, 1987; Scott *et al.*, 1998; Osei *et al.*, 2003). Model performance at the watershed outlet was evaluated using the Nash-Sutcliffe coefficient, NS (Martinez and Rango, 1989), the deviation from measured data, *Dv* (Martinez and Rango, 1989), and the index of agreement, *d* (Willmott, 1984).

The NS – Equation (1) – is a measure of model efficiency that relates simulated values to corresponding measured values.

$$NS = 1 - \left(\frac{\sum_{i=1}^{n} \left(Q_i - Q_i'\right)^2}{\sum_{i=1}^{n} \left(Q_i - \overline{Q}\right)^2} \right) \tag{1}$$

where Q_i is the measured value (stream discharge or pollutant concentration), Q_i' is the simulated value, $\overline{Q}$ is the average measured value, and n = the number of values.

Values of *NS* range from negative infinity to 1; values of *NS* close to 1 indicate improved model performance, while a value of zero indicates that simulated values are no better than taking a mean of observed values.

The *Dv* is a measure of the deviation of simulated values from measured values and is computed as shown in Equation (2). Improved model performance is indicated as the *Dv* approaches zero.

$$Dv = \frac{V' - V}{V} * 100 \tag{2}$$

where V is the measured annual value (streamflow volume or pollutant load) and V' is the simulated annual value.

The value d is a measure of relative error, which indicates the degree to which simulated values match observed values. It is computed as

$$d = 1 - \left(\frac{n * RMSE^2}{PE} \right) \tag{3}$$

where n is the number of values, $RMSE$ is the root mean square error, PE is the potential error variance ($0 \le RMSE^2 \le n^{-1}PE$), and

$$PE = \sum_{i=1}^{n} \left(\left|Q_i - \overline{Q}\right| + \left|Q_i' - \overline{Q}\right| \right)^2 \tag{4}$$

Q_i, Q_i' and $\overline{Q}$ are as previously described.

The index of agreement varies between zero and 1. Values approaching 1 indicate improved model performance and are thus desirable.

In addition to computed performance measures, time series plots of simulated versus measured data were compared.

Determination of Phosphorus Losses From Hydrologic Response Units. Following calibration, the SWAT model was run and annual total phosphorus (TP) and dissolved phosphorus (DP) output obtained for a 10-year period (1987-1996). A period of 10 years was selected to adequately represent climatic pattern variations within the Town Brook watershed while also covering a complete crop rotation. Average annual total and dissolved phosphorus losses were obtained for each HRU. These were then used in the optimization as well as for identifying HRUs that had high phosphorus losses and therefore that were potentially most in need of BMPs. Based on information in Sharpley and Rekolainen (1997), high phosphorus loss HRUs were defined as those from which total and dissolved phosphorus losses exceeded 1.5 and 0.3 kg/ha, respectively.

Quantitative Estimation of BMP Effectiveness

A BMP tool (Gitau *et al.,* 2005) was used to characterize expected BMP effectiveness based on soil and slope conditions within individual HRUs. Developed within a Microsoft Access database, this tool was designed to allow estimates of BMP effectiveness to be made for user specified site soils and slopes. The underlying database was built upon effectiveness data obtained from previous BMP studies containing data on particulate, dissolved, and total phosphorus effectiveness, associated site and study characteristics, and complete literature citations for a variety of agricultural BMPs. At present, effectiveness estimates can be obtained for animal waste systems, barnyard runoff management, conservation tillage, contour strip crop, crop rotations, filter strips, nutrient management plans, and riparian forest buffers. Detailed descriptions of these BMPs as defined in this study are given in Table 1. Conservation tillage was not considered in this study, as temperatures within the study watershed are often too low to allow for proper crop growth under the practice. The practice has thus been excluded from Table 1. Values from the tool represent the average effectiveness of each BMP over its expected lifetime.

Site slopes were represented using slope classes (0-3 percent, 3-8 percent, 8-15 percent, 15-25 percent, 25 percent+) based on ranges for the various soil map units, as documented in the National Soils database. Site soils were represented using the hydrologic soil group (indicator of soil runoff potential) as defined by NRCS (1996).

Using the BMP tool this way, phosphorus reduction effectiveness estimates were obtained that were BMP specific and also reflective of the influence of site slopes and soils on effectiveness. Where data were not available for a soil or slope combination, estimates were obtained by combining means associated with individual soil and slope effects or by considering the average effects for the BMP regardless of slope or soils, as recommended in Gitau *et al.* (2005).

Determination of BMP Costs

Specific BMP cost data and the associated expected lifetime of the BMPs were obtained from Delaware County, New York. BMP cost records (E. Blouin, NYCDEP, 2002, personal communication; G. Lamont, NCRS, 2002, personal communication). The BMP implementation costs as of year 2002 and associated lifetimes are summarized in Table 2. Costs for riparian buffers, for example, included costs of tree establishment, fencing, stream crossings, and incentive payments to the farmer, while costs of nutrient management plans included costs of soil and manure testing and transport and spreading of manure.

To provide a means of comparing BMPs by cost, given their different lifetimes, and to supply cost values consistent with time averaged pollutant load and BMP effectiveness used in this study, all costs were reduced to their annual values. The costs were

TABLE 1. Classes of Best Management Practices (BMPs) as Used in the BMP Tool.

BMP	Description
Animal Waste Systems	Systems designed for proper collection, transportation, and storage of livestock manure and other animal waste.
Barnyard Runoff Management	Exclusion of clean water runoff from barnyard and disposal of remaining barnyard runoff in a way that minimizes its pollution potential.
Contour Strip Crop	Alternating strips of a row crop with a small grain or forage, planted on the contour (contour strip cropping) or across the slope (field strip cropping).
Crop Rotation	A planned sequence of annual and/or perennial crops.
Filter Strips	Strips of perennial grasses, planted across the slope, established adjacent to areas of high pollutant potential and managed for pollutant removal by overland flow.
Nutrient Management Plan	Managing the rate, timing, and placement of fertilizers, manures, and other nutrient sources to encourage maximum nutrient recycling and minimize nutrient runoff and leaching.
Riparian Forest Buffers	Areas of trees, shrubs, and grasses located adjacent to ponds, lakes, and streams to filter out pollutants from runoff and provide shade for fish and wildlife.

TABLE 2. Summarized BMP Costs, Associated Useful Life and Annual Costs for the Various BMPs Evaluated.

BMP Name	Components Included in Cost	Total Cost	Useful Life Years	Annual Cost	Units
Animal Waste System	Collection, transport, storage.	$17,760.00	10	$2,600	$/Facility
Barnyard Runoff Management	Diversion, roof runoff management (gutter and downspout), heavy use area protection (concrete or gravel), screen box, underground outlet, fencing.	$12,165.50	10	$1,800	$/Facility
Contour Strip Cropping	Seeding, other inputs, loss of production, machinery cost	$69.97	10	$24	$/ha
Crop Rotation	Seeding, other inputs, loss of production, machinery cost	$22.23	1	$10	$/ha
Filter Strips	Land grading, vegetation establishment including seed bed preparation and seeding, piping	$2,425.00	10	$360	$/Facility
Riparian Forest Buffers	Tree planting, fences, crossings, incentive payments, alternative watering system	$13,646.75	25	$1,300	$/ha
Nutrient Management Plans	Soil testing, manure testing, manure transportation, spreading	$24.70	1	$27	$/ha

annualized based on Equation (5) (Degarmo *et al.*, 1997).

$$A_{BMP} = \left[\frac{Pr}{\left(1-(1+r/100)^{-n}\right)} \right] \tag{5}$$

where A_{BMP} is the annualized cost of a BMP ($), P is the capital cost of the BMP ($), r is the time value for money, set at 8 percent based on OMB (2003), and n is the lifetime of the BMP (yrs).

Optimization of BMP Selection and Placement

Optimization of BMP selection and placement was carried out using the genetic algorithm, a robust search algorithm capable of generating a number of possible BMP solutions for a watershed (Goldberg, 1989; Chatterjee, 1997; Srivastava, 1999; Veith *et al.*, 2003). The genetic algorithm was configured to utilize average annual total phosphorus or dissolved phosphorus loads as simulated by SWAT, effectiveness data from the BMP tool, and BMP costs for optimizing BMP selection and placement. For this study, the genetic algorithm was set to evaluate scenarios based on the effectiveness in reducing total phosphorus and in reducing costs.

Scenarios. Four BMP implementation scenarios (1 to 4) were examined as follows.

Scenario 1 – The genetic algorithm was set to place BMPs on all cropland and pasture (991 HRUs). However, every cropland and pasture HRU was required to contain at least one BMP.

Scenario 2 – The genetic algorithm was set to place BMPs on all cropland and pasture HRUs to the extent that placing a BMP on an HRU helped improve the overall effectiveness of a BMP solution.

Scenario 3 – This scenario was set up to evaluate the impact of optimizing only high phosphorus loss HRUs (i.e., only those HRUs for which losses were expected to equal or exceed the total and dissolved phosphorus thresholds described previously). The genetic algorithm was thus required to place at least one BMP on each high phosphorus loss HRU.

Scenario 4 – This scenario comprised the basic BMP implementation scheme within the watershed resulting from the whole farm planning process – all cropland in a rotation, all fields having a nutrient management plan, and all barnyard areas having a barnyard runoff management system, with filter strips added as treatment for barnyard runoff. BMPs for this scheme are fixed; thus no optimization was carried out for this scenario.

Scenario Evaluations. In general, within the genetic algorithm, the degree to which the various scenarios meet pre-established objective criteria is determined through fitness functions. For the methodology described in this paper, the objective was to determine BMP solutions for which a user defined phosphorus reduction target was met and then minimize costs. Two fitness functions were defined based on work by Veith *et al.* (2003) and Gitau *et al.* (2004): one rated the effectiveness with which the scenario could reduce phosphorus loads (P_{score}), and the other rated the cost reducing potential for the scenario (C_{score}). Overall scenario performance was evaluated by combining the phosphorus and cost scores into one objective function, herein termed the fitness score (F_{score}), and calculated as

$$F_{score} = \begin{cases} P_{score} & \text{if } P_{score} < 1 \\ C_{score} & \text{if } P_{score} = 1 \end{cases} \tag{6}$$

where F_{score} is the fitness score and P_{score} and C_{score} are the phosphorus and cost scores, respectively, defined as follows.

The phosphorus score (P_{score}) was calculated as

$$P_{score} = \begin{cases} 1 & \text{if } P_s \leq P_t \\ \dfrac{P_b - P_s}{P_b - P_t} & \text{if } P_t < P_s < P_b \\ 0 & \text{if } P_s \geq P_b \end{cases} \tag{7}$$

where P_{score} is the phosphorus score, P_s is the average annual total phosphorus load for the scenario being evaluated (kg), P_b is the average annual baseline total phosphorus load (kg), and P_t is the average annual target total phosphorus load (kg).

Using Equation (7), for a hypothetical baseline load of 1,000 kg and target load of 500 kg, a scenario load of 500 kg or less would yield a P_{score} of 1, a scenario load of 700 kg would yield a P_{score} of 0.6, while a scenario load greater than 1,000 kg (indicating that the BMPs could cause a net increase in total phosphorus) would yield a P_{score} of zero.

For the Town Brook watershed, the baseline total phosphorus load (P_b) was the total load from the watershed (3,900 kg) in the pre-BMP state, calculated by totaling average annual loads (kg) from each HRU in the watershed. The target load (P_t) is defined as the total phosphorus loss expected after implementation of BMPs. This is a user defined target that can be set depending on the pollutant reduction goals in the area concerned. For this study, the target load was initially calculated based on guidelines for desirable total phosphorus concentrations in rivers and streams, 10 µg/l (USEPA, 2000), which is based on background levels in pristine streams in the ecoregion associated with Town Brook watershed (Ecoregion XI – Central and Eastern Forested Uplands). This background concentration was converted to a target load of 250 kg based on the daily average flow rate for Town Brook watershed, 0.79 m^3/s. On running the genetic algorithm, however, it was found that this target could not be attained by the BMPs being evaluated. This target was subsequently reset to 1,560 kg, corresponding to a load reduction of 60 percent from the baseline. The value of 60 percent was selected as it was close to the average and median value (about 50 percent) of the effectiveness of the BMPs being investigated and was thus thought to be achievable.

The scenario load (P_s) was calculated within the genetic algorithm by multiplying the baseline load for each HRU with a corresponding loss factor calculated from the BMP effectiveness estimates obtained from the BMP tool and summing resulting HRU loads over all HRUs in the watershed as

$$P_s = \sum_{i=1}^{n} \left(1 - E_{BMP,HRU}\right) P_{bi} \tag{8}$$

where P_s is the total phosphorus loss from the watershed following BMP implementation (kg), P_{bi} is the baseline total phosphorus load (kg) for the ith HRU, $E_{BMP,HRU}$ is the BMP effectiveness (decimal) dependent on the BMP and site characteristics of the HRU, (1-$E_{BMP,HRU}$) is the loss factor, and n is the number of HRUs.

The loss factor defines the percentage of the P_{bi} that is still lost following BMP implementation. Where no BMPs were placed, the $E_{BMP,HRU}$ was equal to zero; thus the P_s was the same as the baseline loss for that HRU.

The BMP effectiveness estimates, $E_{BMP,HRU}$, are specific to the BMP. These estimates are also HRU specific, as they are obtained based on HRU soil and slope conditions. Thus it should be noted that for any particular BMP, HRUs with the same soil and slope conditions will have the same value of BMP effectiveness associated with them. Where BMP combinations were used, combined BMP effects were approximated by assuming sequential passage of pollutant from one BMP to another, as recommended by Gitau *et al.* (2005); each succeeding BMP thus exerted its specific reduction on "incoming" phosphorus load. While this probably led to a slight overestimation of combined BMP effects, it did serve to provide information on the relative effectiveness of BMP combinations. These values were also used across all scenarios evaluated, thus allowing reasonable scenario evaluations.

The cost score (C_{score}) was calculated as

$$C_{score} = \begin{cases} 2 & \text{if } C_s = C_b \\ 1+\dfrac{C_m - C_s}{C_m - C_b} & \text{if } C_b < C_s < C_m \\ 1 & \text{if } C_s \geq C_m \end{cases} \tag{9}$$

where C_{score} is the cost score, C_s is the scenario cost increase ($), C_b is the baseline cost increase ($), and C_m is the maximum allowable cost increase ($).

Thus, by Equation (9), for a hypothetical maximum allowable cost increase of $100,000 and a baseline cost increase of $20,000, scenario cost increases less than or equal to $20,000 would yield a C_{score} of 2, a scenario cost increase of $40,000 would yield a C_{score} of 1.5, while a scenario cost increase greater than or equal to $100,000 would yield a C_{score} of 1. Scores closer to 2 are desirable; thus this function serves to preclude solutions for which costs would exceed allocated funds while encouraging lower cost scenarios by penalizing solutions that come close to the cost maximum.

For the Town Brook watershed, the baseline cost increase (C_b) was set at zero to reflect a case in which there were no additions to conventional practices. The baseline cost increase can also be set to the targeted cost of BMP interventions such that solutions determined using the genetic algorithm would have costs varying between the target and a pre-set maximum cost.

The maximum allowable cost increase (C_m) defines the maximum amount of money that can be spent over the watershed on BMPs. In Delaware County, New York, maximum costs are decided on a farm-by-farm basis based on a predetermined pollution potential risk of the farm and the number of animal units on the farm or for nonlivestock farms based on the farm area in acres (G. Lamont, NRCS, 2003, personal communication). For the Town Brook watershed, a maximum cost estimate for the watershed was determined based on the number of animal units in the watershed and assuming an overall medium risk for the watershed, giving a value of $167,000 per year.

Scenario cost increases were calculated within the genetic algorithm by calculating the cost of having a selected BMP or BMP combination within an HRU and totaling BMP costs for all the HRUs within the watershed. Where no BMPs were applied, the BMP cost was zero.

Cost Effectiveness. For each of Scenarios 1, 2, and 3, the genetic algorithm was set to output 15 best solutions based on overall fitness score and, for each solution, the associated BMP selections on an HRU basis and the associated fitness scores. These 15 solutions provided alternatives for BMP selection and placement associated with each scenario that may all be used to meet the phosphorus target at minimum costs. For this study, the most fit solution (that is, the solution with the highest fitness score) for each of Scenarios 1 through 3 was selected for further analyses. For the most fit solutions, the genetic algorithm returned associated total phosphorus loads and scenario cost increases, in addition to the associated BMP selections and fitness scores. These total phosphorus load and cost outputs were used in calculating scenario cost effectiveness, defined as the annual cost ($) of removing a kilogram of P.

RESULTS AND DISCUSSION

A methodology was developed for evaluating BMP solutions with a view to determining optimal scenarios for BMP selection and placement. The Town Brook watershed was used to illustrate the approach. The methodology combines average annual phosphorus losses as simulated by SWAT, BMP effectiveness estimates from a BMP tool, and BMP costs in optimizing BMP selection and placement using a genetic algorithm. Watershed phosphorus losses were characterized on an individual HRU basis, BMP effectiveness and BMP costs were determined, and finally various BMP solutions were evaluated to determine optimal scenarios for BMP selection and placement.

Characterization of Phosphorus Losses From Individual Response Units

Table 3 shows simulated HRU level sediment and phosphorus loads summarized by the various land uses in the watershed. These are shown in comparison to watershed estimates made by Delaware County personnel and to literature-based estimates. Table 4 shows performance statistics computed for model calibrations and validations. The study used average annual loadings; hence calibrations and validations are discussed mainly on an annual time period basis. Sediment losses simulated from the various land use areas were within the range of watershed and literature-based estimates (Table 3). The relative magnitudes of losses from the various land uses were also consistent with expectations, with highest losses coming from cropland and the lowest from forested lands. Thus, the model appears able to simulate pollutant losses on an HRU basis.

TABLE 3. Comparison of SWAT Simulated Average Annual Sediment and Phosphorus Losses to Watershed Wide and Published Estimates.

Component	Simulated Value	Watershed Wide* and Published Estimates	Source
		Sediment (tonnes/ha/yr)	
Cropland	19.20	20-25	Lamont (2003), Pers. Comm.
Pasture	1.66	1.73 and <2.50	CCE** (1987) Lamont (2003). Pers. Comm.
Forest	0.83	0.99	CCE (1987)
		Dissolved P – Phosphorus (kg/ha/yr)	
Hay/Pasture	0.18 / 0.31	0.08 - 2.00	Osei *et al.* (2003)
Watershed	0.16	0.14	Scott *et al.* (1998)
		Total P – Phosphorus (kg/ha/yr)	
Hay / Pasture	2.09 / 1.24	0.4 - 6.96	Osei *et al.* (2003)

*Estimates made by watershed personnel.
**Cornell Cooperative Extension.

TABLE 4. Watershed Outlet Performance Statistics for Hydrology, Sediment and Phosphorus Calibrations and Hydrology Validations Carried Out on an Annual Time Step.

Component	NS*	Dv**	d***
Streamflow Volume (mm) Calibrations	0.98	0.05	0.99
Streamflow Volume (mm) Validations	0.98	0.06	0.99
Instream Sediment (kg/yr) Calibrations	0.66	-0.29	0.91
Instream Total Phosphorus (kg/yr) Calibrations	0.44	-0.32	0.72
Instream Dissolved Phosphorus (kg/yr) Calibrations	-0.91	-0.58	0.58

*Nash-Sutcliffe coefficient ($-\infty \leq NS \leq 1$, values closer to 1 preferable).
**Deviation ($0 \leq Dv \leq 1$, low values preferable).
***Degree of agreement ($0 \leq d \leq 1$, higher values preferable).

Based on evaluations at the watershed outlet (Table 4), the model performed well for hydrology simulations ($NS > 0.9$; maximum $Dv = 0.06$, $d \approx 1$) and performed adequately for instream sediment simulations (NS = 0.66, Dv = -0.29; d = 0.91). The model tended to underpredict instream total and dissolved phosphorus loads (Dv = -0.32 and -0.58, respectively), with dissolved phosphorus concentrations being predicted less accurately than those of total phosphorus (Figure 3b,c; Table 3). Underprediction of total phosphorus was expected due to the multiplicative effect of the calibrated model, which underpredicted stream sediment and thus sediment bound P. Underprediction of dissolved phosphorus was thought to be attributable to desorption of phosphorus from bed sediments, which was not reflected in the simulations since stream processes were not simulated in this study. However, the model adequately simulated phosphorus losses from the various HRUs and the associated land use areas based on Table 3. As BMP evaluations were carried out on an HRU basis, model performance was considered adequate for subsequent evaluations.

Table 5 presents a summary of phosphorus losses from the various land uses within the watershed and as averaged over the watershed based on a 10-year simulation performed using the calibrated model. From the table, the simulated average annual dissolved phosphorus loss of 0.16 kg/ha determined for the watershed was close to the value of 0.14 kg/ha/yr determined within the New York City watersheds region and documented by Scott *et al.* (1998). Simulated average annual total and dissolved phosphorus losses for hay and pasture were also within the ranges for edge of field losses (0.4 to 6.96 kg/ha/yr and 0.08 to 2.00 kg/ha/yr, respectively) for dairy waste-applied grass areas, as documented by Osei *et al.* (2003). Thus, simulated losses compared well to expected losses as documented in the literature.

Figure 4 shows the distribution of phosphorus losses over the watershed. HRUs losing more than the predefined 0.3 kg/ha of dissolved phosphorus and 1.5 kg/ha of total phosphorus were considered to have high phosphorus losses and were thus most in need of

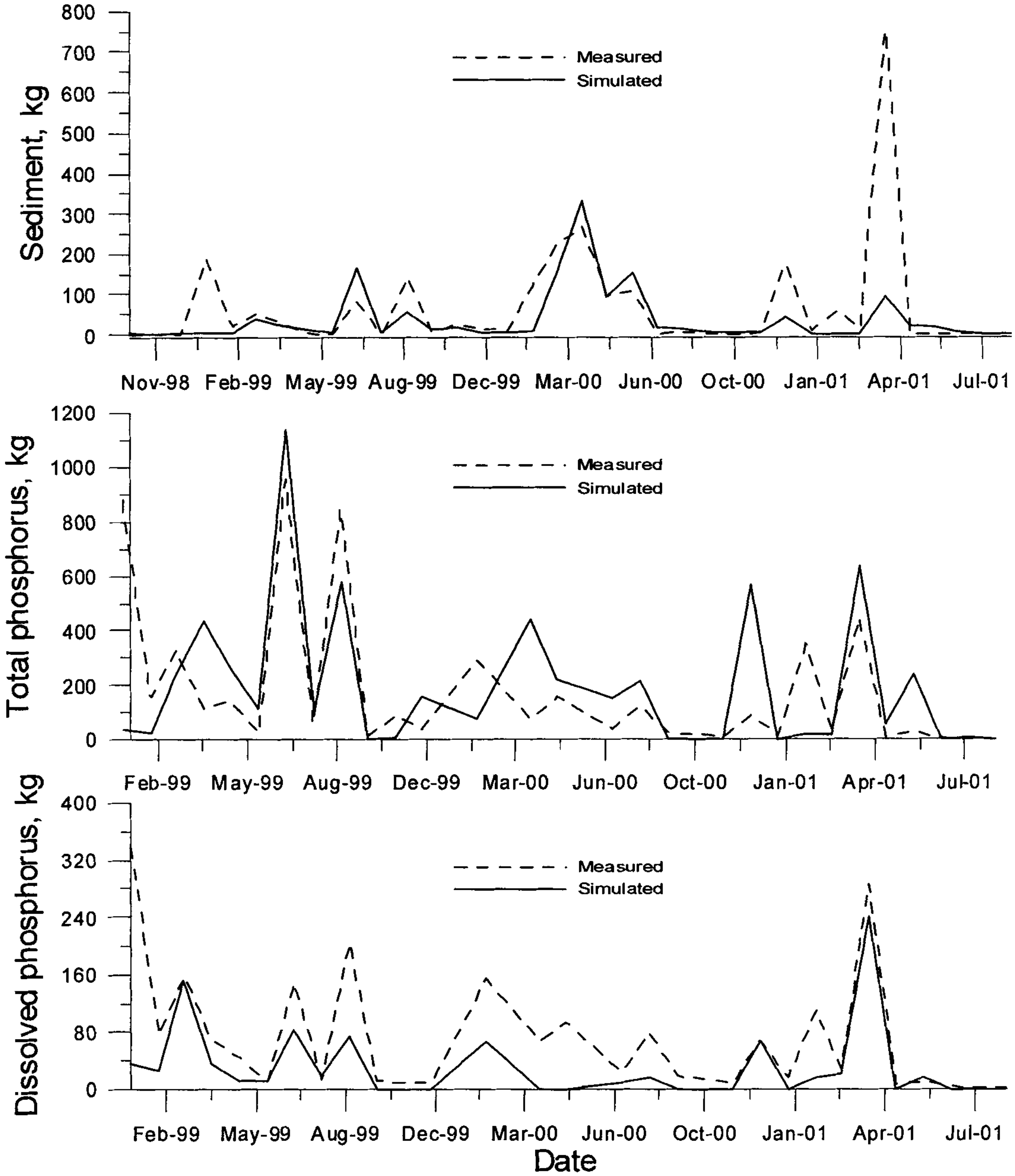

Figure 3. SWAT Monthly Simulations Comparing Sediment, Total Phosphorus (TP), and Dissolved Phosphorus (DP) to Observed Data.

TABLE 5. Summary of Simulated 10-Year Baseline Average Annual Phosphorus Load Data Used in Optimizing BMP Selection and Placement.

Land Use	Dissolved Phosphorus (kg/ha)	Total Phosphorus (kg/ha)
Hay	0.15	2.16
Pasture	0.27	1.35
Corn	0.34	5.43
Forest	0.01	0.19
Watershed	0.14	1.06

BMPs. Based on these thresholds, 689 HRUs were found to exceed at least one of the thresholds. Since SWAT does not recognize the spatial positioning of HRUs, nor does it route pollutants between HRUs, some of the near stream HRUs as modeled were not selected as having high P-losses (Figure 4). In reality, it is expected that near stream HRUs would have disproportionately high phosphorus losses, based on information in Dunne and Black (1970), Freeze (1974), and Gburek and Sharpley (1998). Thus, any cropland or pasture near stream HRU that had not

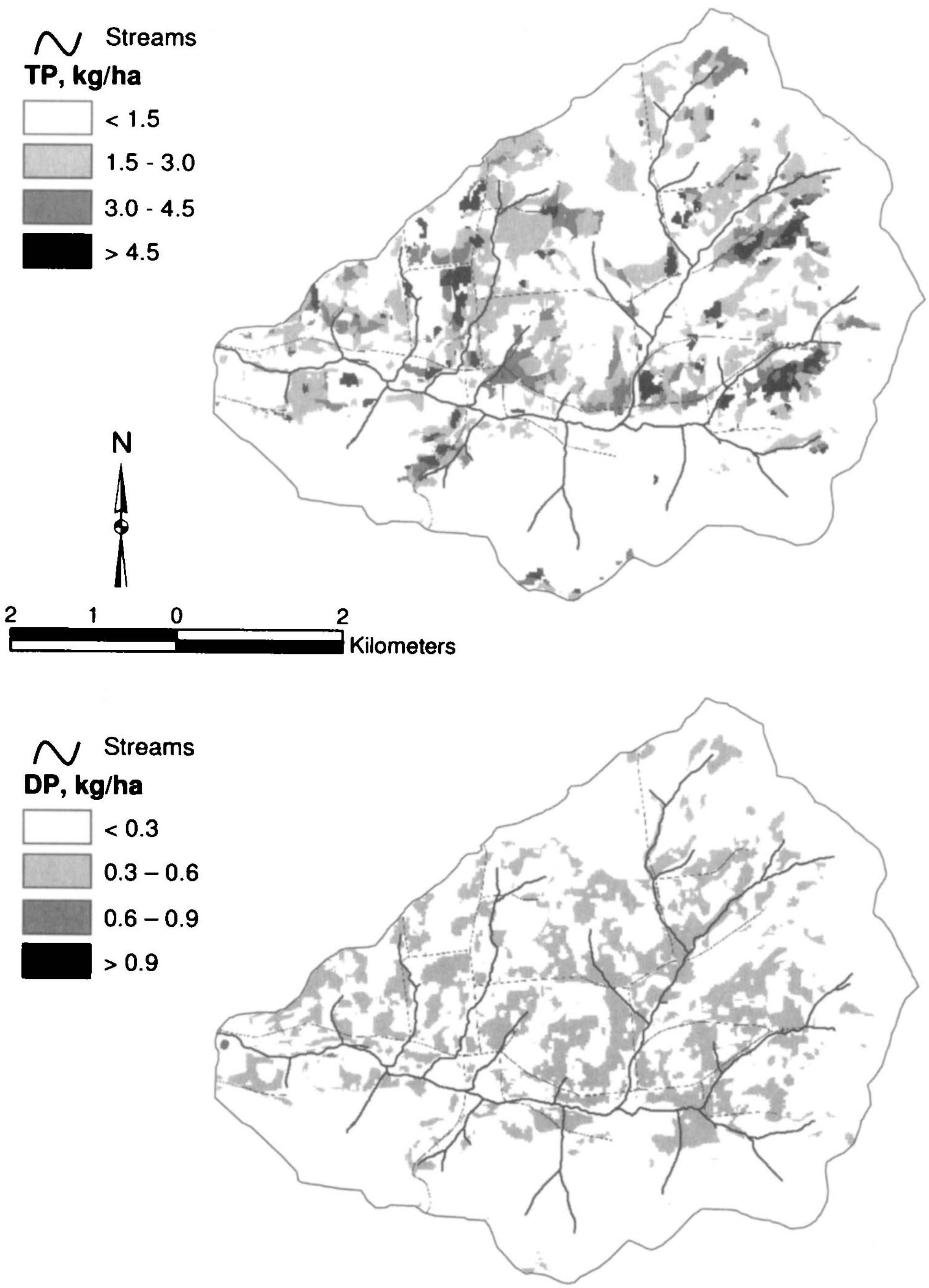

Figure 4. Distribution of Average Annual Phosphorus Losses From Individual HRUs. HRUs from which average annual losses exceed 1.5 kg/ha of total phosphorus and 0.3 kg/ha dissolved phosphorus are considered most in need of BMPs.

been included based on the preidentified thresholds was added. With the addition of near stream HRUs, all cropland and pasture HRUs in the watershed (991 HRUs) were candidates for BMP allocation. Forest and road land uses were fixed as not needing BMPs, regardless of the losses from these regions.

BMP Effectiveness Estimates

Table 6 shows example effectiveness estimates determined from the BMP tool. In some cases, there were not enough data corresponding to a specific slope and/or soil to allow for a site specific estimate to be

TABLE 6. Sample BMP Effectiveness as Obtained From the BMP Tool.

BMP Name	Slope	Hydrologic Soil Group	Dissolved Phosphorus (percent)	Total Phosphorus (percent)
None			0.0	0.0
Animal Waste Storage	N/A		-30	42
Barnyard Runoff Management	N/A		30	51
Crop Rotation	3-8	B	43	58
Contour Strip Crop	8-15	C	32*	48
Filter Strips	N/A		26	54
Nutrient Management Plan	3-8	C	64	56
Nutrient Management Plan (average**)			25	51
Riparian Forest Buffers (average**)			62	40

*Estimated by averaging separate but corresponding slope and soil specific effectiveness.
**An average value calculated for the BMP can be used where data corresponding to site slope and soils are not sufficient to provide a site specific estimate.

obtained. In such cases an estimate of overall average BMP effectiveness regardless of slope and soils was used. In other cases, for instance with barnyard runoff management and associated filter strips, breaking the information down by site characteristics was deemed inapplicable, indicated by the "N/A" in Table 6. In this study, filter strips were considered only as treatment for barnyard runoff since these are not used as edge of field BMPs within Town Brook watershed.

Optimization of BMP Selection and Placement

For the Town Brook watershed, results of the optimization favored implementation of nutrient management plans and crop rotations in combination with contour strip cropping (Figure 5). In addition, the genetic algorithm favored the use of riparian buffers within the watershed. Typical crop rotations involve three years of corn and five years of hay in sequence, while strip cropping consists of alternating strips of a row crop with a small grain crop or forage planted along the contour or across the slope. Nutrient management plans involve the application of plant nutrients in the correct amount and form to minimize adverse impacts on water quality while still meeting crop requirements. Table 7 shows a comparison of typical nutrient management plans with conventional approaches.

In Scenario 1, about 1,500 ha were placed in nutrient management plans, crop rotations, and contour strip cropping, either alone or in combination, with more than 1,200 ha placed in nutrient management plans and a combination of crop rotations and contour strip cropping. With Scenarios 2 and 3, the genetic algorithm placed 1,000 ha and 800 ha, respectively, in nutrient management plans and a combination of crop rotations and contour strip cropping. In each of Scenarios 1, 2, and 3, nutrient management plans covered the largest area. Buffers were selected for 55, 63, and 96 near stream HRUs for Scenarios 1, 2, and 3, respectively, covering an area of 9 ha, 17 ha, and 45 ha, respectively. Filter strips as treatment for barnyard runoff were selected in Scenarios 1 and 3. With Scenario 4, all BMPs were fixed; all cropland HRUs received crop rotations and nutrient management plans, all pastures had nutrient management plans, and all barnyard areas had barnyard runoff management systems and filter strips. No other BMPs or combinations were considered for this scenario.

With the BMPs acting together in the watershed, total phosphorus losses could potentially be reduced by up to 60 percent for each of Scenarios 1, 2, and 3; thus all scenarios offered equal benefits as far as pollutant reduction benefits were concerned. For each of Scenarios 1 to 3, the genetic algorithm distinctly favored nutrient management plans and contour strip cropping in combination with crop rotations over other combinations of on-field BMPs. This indicates that these particular BMPs probably need to be on the landscape at the same time. However, since the areas in these BMPs decreased from Scenarios 1 to 3 yet the overall effectiveness in reducing phosphorus was the same for all scenarios, the results suggest that as far as pollutant reduction benefits are concerned, BMPs do not necessarily have to be implemented everywhere on the watershed; rather, they can be implemented selectively to areas most in need of the BMPs.

Table 8 shows a comparison of fitness scores, cost increases, and cost effectiveness for the three BMP

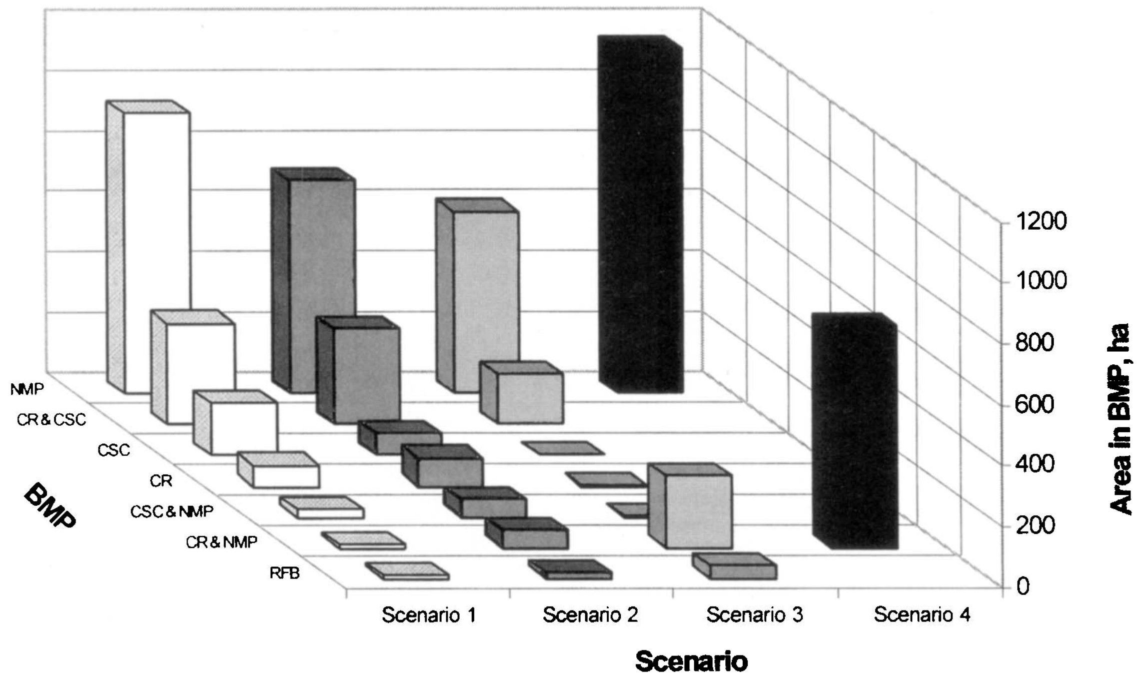

Figure 5. A Comparison of BMP Allocations, Based on Area in Each BMP, for the Four Scenarios Investigated. (CSC: Contour strip crop; CR: crop rotation; NMP: nutrient management plan; RFB: riparian forest buffers; CR and CSC, CSC and NMP, CR and NMP: combinations of the BMPs as defined.)

TABLE 7. A Comparison of Nutrient Management Planning With Conventional Approaches for Manure Spread Fields.

Component	Conventional	Nutrient Management Plan
Present Nutrient Levels in Soil	Not determined	Determined for each field
Pollution Risk Level	Not determined	Determined for each field
Application Dates	Daily	Based on risk level Risk level 1 – May be applied year round Risk level 2 – April to December Risk level 3 – May to October Risk level 4 – No spreading
Hydrologically Sensitive Areas	Not considered	Manure not spread within 30 m (100 ft) of these areas
Application Rates	Not defined	Not to exceed maximum recommended rate, typically 50-63 tons/ha/yr (20-25 tons/acre/yr) for corn and 37-50 tons/ha/year (15-20 tons/acre/yr) for hay. Maximum recommended rate based on supplying crop requirements for priority nutrient.
Application Method	Surface applied	Best application method determined.

selection and placement scenarios investigated in comparison to the basic scenario (Scenario 4). Because BMP costs as used in this study did not include operation and maintenance costs, the cost effectiveness of the various scenarios may vary in their absolute amounts if these were included. The results presented herein should therefore be taken in an illustrative sense.

From Table 8, the highest fitness score was observed with Scenario 1, and the lowest was associated with Scenario 4. The fitness score for Scenario 4 was less than 1, indicating that the pollutant target was not met with this scenario (Equation 9). The pollutant target was attained for all the other scenarios (fitness score > 1), with the differences in scores due to differences in costs.

TABLE 8. Fitness Scores, Cost Increases, and Cost Effectiveness of the Three BMP Selection and Placement Scenarios Investigated in Comparison to the Basic Scenario (Scenario 4).

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Fitness Score (F_{score}) (dimensionless)*	–	1.67	1.65	1.44	0.99
Total Phosphorus (TP) Loss (kg)	3,900	1,560	1,560	1,560	1,580
Total Phosphorus Reduction From Baseline (kg)	–	2,340	2,340	2,340	2,320
Scenario Cost Increase From Baseline ($/year)	–	55,000	59,000	94,000	78,000
Cost Effectiveness ($ spent/kg total phosphorus removal/year)**	–	24	25	40	34

*The fitness score ($0 \leq F_{score} \leq 2$) measures degree to which a scenario meets pre-established objective criteria; higher values indicate increased fitness.
**Cost effectiveness is calculated by dividing scenario cost increase by phosphorus reduction from the baseline.

While there were fewer BMPs associated with Scenario 4 than with the other three scenarios, cost increases associated with Scenario 4 were relatively high. The higher costs were attributed to the requirement that all barnyard areas have barnyard runoff management. Optimization did not favor the use of barnyard runoff management BMPs; these are costly, and the potential pollutant reduction benefits associated with them may not be commensurate with their costs.

Overall, Scenario 1 offered the most cost effective solution, with a cost effectiveness of $24/kg total phosphorus removal per year compared to the $34/kg total phosphorus removal per year associated with the basic scenario. Scenario 2 was only slightly less cost effective than Scenario 1. While the pollutant target was attained in Scenario 3, this scenario was the least cost effective, at $40/kg total phosphorus removal per year. In this scenario, the genetic algorithm had been set to place BMPs only on selected high phosphorus loss HRUs. Results then suggest that while selective BMP implementation may offer the same pollution-reducing benefits as would implementing BMPs on all cropland areas, selective implementation may not offer the most cost effective solution.

Figure 6 shows BMP placement in the basic scenario as compared to the most fit scenario (Scenario 1). In Scenario 2, the genetic algorithm favored the less costly combination of crop rotations with strip cropping, while the basic scenario combined rotations with nutrient management plans. Placement of nutrient management plans (not in combination with other BMPs) was similar for Scenarios 1 and 4. Scenario 1 included riparian buffers, which were not part of the basic scenario, while Scenario 4 included barnyard runoff management BMPs, which were not favored by the genetic algorithm.

SUMMARY AND CONCLUSIONS

This study showed that BMP solutions can be evaluated based on their phosphorus reducing potential and on costs by using an optimization approach. The optimization approach not only gives an indication of the potential effectiveness of BMPs on a watershed wide basis, it also provides alternatives for BMP selection and placement for individual response units within the watershed, thus allowing BMPs to be placed where they are likely to have the most impact. As was the case in this study, each BMP scenario evaluated had a different cost-effectiveness associated with it. Additionally BMP solutions for which the phosphorus target was not met (other than the basic scenario) were not discussed in this paper, yet these did exist. This study suggests that there is a need to evaluate potential BMP solutions prior to implementation in order to preclude solutions that are unlikely to offer adequate pollutant reduction benefits. The methodology so developed offers a means of generating and evaluating these solutions. It should be noted that results presented in this paper are specific to the Town Brook watershed and as such cannot be directly applied to any other watershed. This methodology is, however, extendable to the Cannonsville Reservoir watershed and to the larger New York City watersheds as well as to other watersheds for which BMPs are being considered.

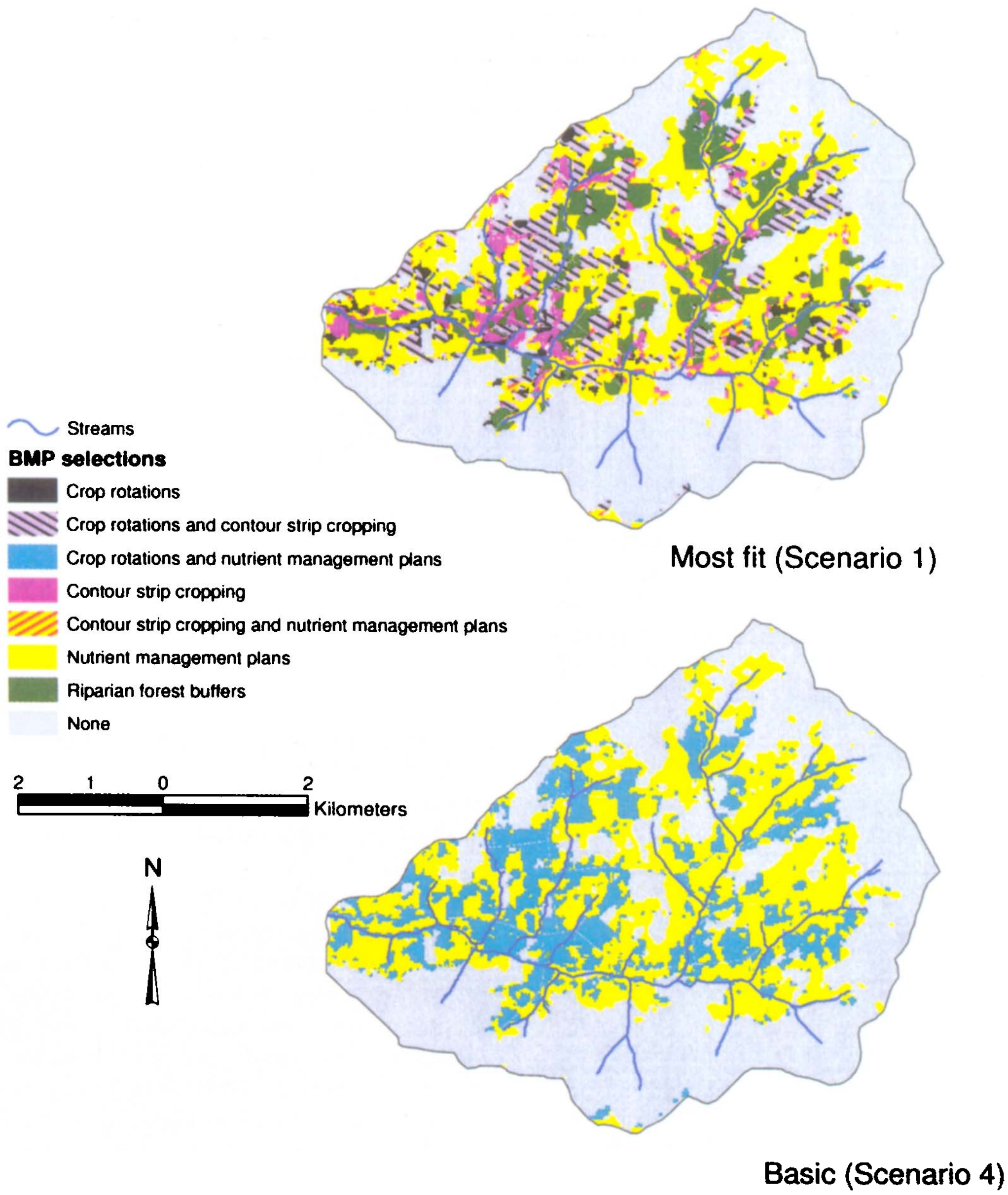

Figure 6. Optimal Scenario for BMP Selection and Placement in Comparison With Basic Scenario. With basic scenario, all fields must have a nutrient management plan, all cropland is in rotation, and all barnyards have barnyard runoff management and filter strips (not shown in the figure, as these would not be visible at this scale).

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